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ONGOING SPACE NUCLEAR SYSTEMS DEVELOPMENT IN THE UNITED STATES

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ABSTRACT

Reliable, long-life power systems are required for ambitious space exploration missions. Nuclear power and propulsion options can enable a bold, new set of missions and introduce propulsion capabilities to achieve access to science destinations that are not possible with more conventional systems. Space nuclear power options can be divided into three main categories: radioisotope power for heating or low power applications; fission power systems for non-terrestrial surface application or for spacecraft power; and fission power systems for electric propulsion or direct thermal propulsion. Each of these areas has been investigated in the United States since the 1950s, achieving various stages of development. While some nuclear systems have achieved flight deployment, others continue to be researched today. This paper provides a brief overview of historical space nuclear programs in the U.S. and provides a summary of the ongoing space nuclear systems research, development, and deployment in the United States.

1. INTRODUCTION

Space exploration, both robotic and human, has been significantly enhanced by the use of nuclear technologies to either power or heat scientific instruments, spacecraft, or rovers. Although nuclear propulsion systems have not yet been demonstrated in flight systems, significant research, development and testing has been conducted on the use of nuclear technology for either direct thermal or electric propulsion. Near-Earth applications have primarily relied on chemical propulsion systems and solar power. However, as we reach further into space, solar power options no longer provide sufficient power within a reasonable size and mass as the solar flux decreases, and chemical propulsion systems are limited in their reach due to the limited energy that can be released by breaking the chemical bonds in the fuel. Other options, such as nuclear power and propulsion systems, can provide ample power for these missions. Traditional chemical propulsion systems would still be used to reach Earth orbit, at which point a nuclear propulsion system could be engaged for the remainder of the transit.

2. RADIOISOTOPE POWER SYSTEMS

The year 2011 marks the 50th anniversary of the use of nuclear power systems in space. The Transit 4A satellite, launched June 29, 1961, was the first spacecraft to carry a radioisotope power system, the SNAP-3B7, which had an initial power of 2.7 We and operated for 15 years [1]. Since that time, a total of 26 U.S. space missions have used radioisotope power sources (RPS). Some of the RPS-powered missions also included radioisotope heating units (RHUs), and a few missions only incorporated RHUs for instrument heating, with power being provided by alternate sources. RPSs have been used to power a number of mission needs, including near-Earth navigation systems, meteorological satellites, and communications satellites; to heat or power sensitive instruments on the Lunar or Martian surface; and to provide power for outer planet missions and to study the polar regions of the Sun. Radioisotope Thermoelectric Generators (RTGs) have demonstrated efficiencies ranging from 4 to 7%, long-lived performance, and high reliability.

Several of the Apollo missions incorporated radioisotope technologies to endure the long (14-Earth-day), cold lunar nights and lunar dust. The Apollo Lunar Surface Experiments Packages (ALSEPs) were powered by SNAP-27 RTGs and were emplaced on the Moon by the crews of Apollo 12, 14, 15, 16 and 17. A few missions, including Apollo 11, Mars Pathfinder, and Mars Exploration Rovers, have used RHUs to withstand the temperature swings during the Lunar and Martian nights, with power being provided by other sources. The MERs, for instance, used a combination of solar arrays and Li-ion batteries for power, but 8 RHUs provided 1 W of thermal energy to keep the instruments between -40^{o}C to +40^{o}C.

All RTGs launched by the United States have met their original mission requirements, and many have operated (and continue to operate) significantly beyond the design mission lifetime. The two Voyager spacecraft, for instance, were launched in 1977. Each spacecraft carried three multi-hundred watt (MHW) RTGs, each of which produced approximately 158 We at the beginning of life. MHW-RTGs adopted Si-Ge thermoelectric elements (unicouples), offering higher temperature operation than the telluride-based thermoelectric elements used previously. Originally intended for the exploration of Jupiter, Saturn, and their satellites, Voyager 2 was retargeted for studies of Uranus and Neptune. Both spacecraft have passed Pluto and are now at the edge of the heliosphere, where they are sending back ground-breaking data that is redefining our understanding of the boundary between the sun's influence and interstellar space [2], more than 33 years after they were launched.

The Galileo spacecraft, launched in 1989 on a mission to orbit Jupiter, and the European Space Agency Ulysses spacecraft, launched in 1990 to explore the polar regions of the Sun, were the first to use the General-Purpose Heat Source RTG (GPHS-RTG). The GPHS-RTG was built on the heritage of the Si-Ge thermoelectric technology used in the MHW-RTGs and was intended for use on multiple missions. GPHS-RTGs have, in fact, been used on Galileo, Ulysses, Cassini (launched in 1997 to study Saturn), and New Horizons (launched in 2006 to study Pluto and Kuiper Belt Objects). The New Horizons mission continues on its way to Pluto, which it is expected to reach in 2015.

The next RPS will be launched in November 2011 as the power source for the Curiosity rover that will explore the Martian surface as a part of the Mars Science Laboratory (MSL). An illustration of the MSL and Curiosity rover is provided in Fig. 1 [3]. The RPS, a 110 We Multi-Mission Radioisotope Thermoelectric Generator (MMRTG, Fig. 2), is the first of a new design that will power the MSL platform and scientific instruments. Where the predecessor RTGs used 18 GPHS modules to provide ~250 We at beginning of life (BOL), the MMRTG incorporates 8 GPHS modules to provide 123 We at BOL. The MMRTG, which was assembled at the Idaho National Laboratory, has been transported to the NASA Kennedy Space Center and has undergone a variety of tests, including a hot fit check with the Rover. The RPS now awaits final integration with the Curiosity rover for launch on an Atlas V in November 2011.

Even before the launch of the Mars Science Lab, engineers are working on the next radioisotope system – the Advanced Stirling Radioisotopic Generator (ASRG). The ASRG will mark the first application of a dynamic power conversion system for any nuclear power source in space. A flight-like engineering unit ASRG was tested in early 2008. The next step toward mission use is qualification of the ASRG, which will include building, fueling and testing an ASRG equivalent to that which would be used on a flight system. An ASRG could be available for NASA missions as early as 2015 once the qualification step is completed [4].

Figure 1. Illustration, Mars Science Laboratory.

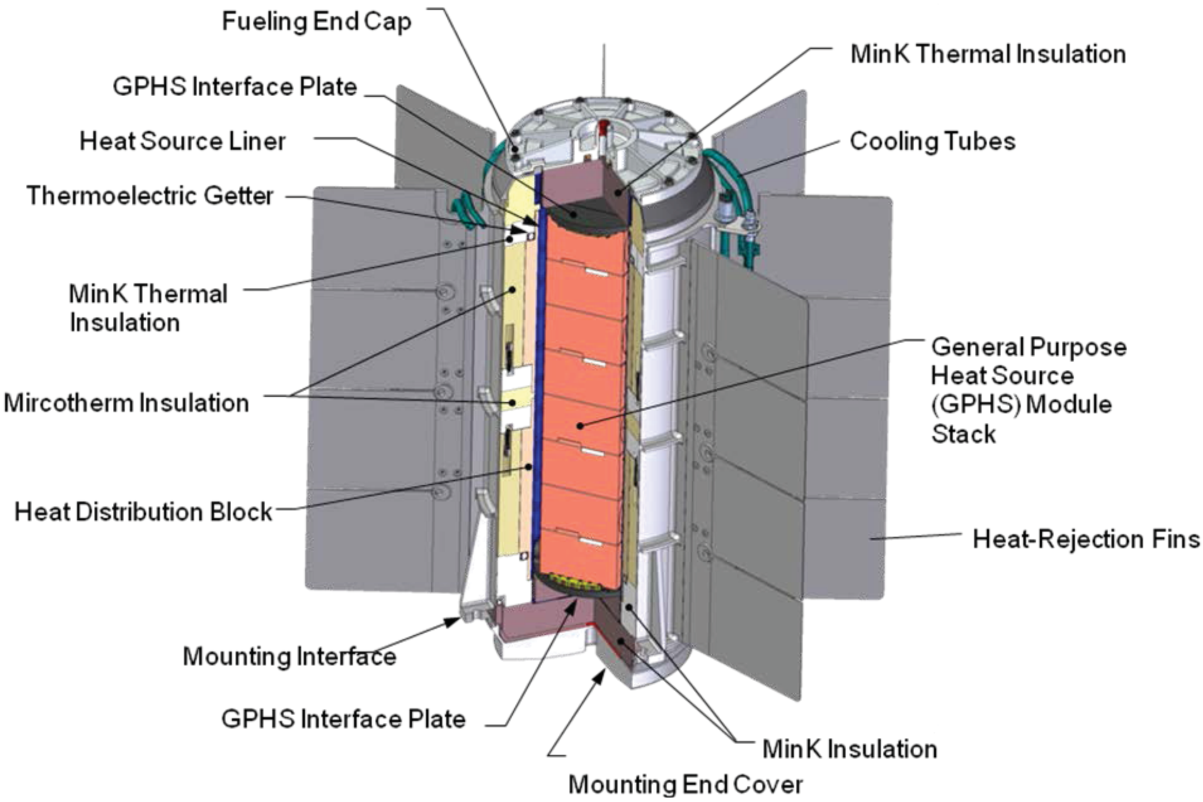


Figure 2. Illustration, MMRTG.

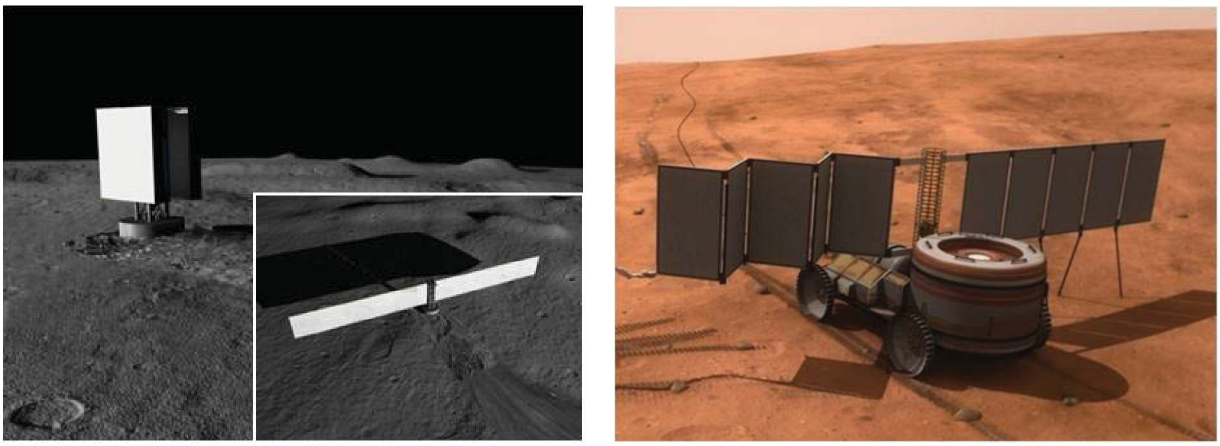
3. FISSION POWER SYSTEMS

Although fission systems for both power and propulsion applications have been investigated many times over the past half century, the U.S. has launched only one fission reactor, the SNAP-10A, in 1965. In contrast, the former Soviet Union flew 31 (possible 33) “BUK” reactor power systems to power Radar Ocean Reconnaissance Satellites (RORSATs) from 1970 to 1988 and two “TOPAZ” reactors to power the Cosmos 1818 and 1867 missions in 1987; only two Earth-orbiting spacecraft and two lunar rovers powered by RPS were launched by the former USSR [1,5]. The summary of fission power systems included herein only touches on a few of the more prevalent research and development programs and does not seek to review all programs that have been initiated in the U.S.

The Systems for Nuclear Auxiliary Power (SNAP) program commenced in 1957 with the development of a U-ZrH thermal reactor system. Although six U-ZrH systems were constructed and tested before the program was terminated in the early 1970s, only the SNAP-10A was flight tested. A few months prior to launch of the flight system, FS-4, a 1-year full power ground test was initiated on a parallel unit, the FS-3. Using an Atlas-Agena launch vehicle, the FS-4 achieved orbit and operated at 50 kWt and 500 We via a thermoelectric power conversion system for 43 days before it was prematurely shut down due to a failure of a voltage regulator in the Agena vehicle.

Perhaps one of the most prevalent, recent forays into development of space nuclear power systems in the US was the Space Power 100-kWe (SP-100) reactor power system, designed and tested in the mid-1980s to early 1990s. The SP-100 was a fast spectrum, lithium-cooled reactor design that incorporated thermoelectric power conversion to produce 100 kWe (~4% conversion efficiency) over a lifetime of 7-10 years. Although the program was terminated in 1994 before the system design was finalized, a series of benchmark critical experiments was completed for generic SP-100 reactor designs in 1986, and Engineering Mock-up Criticals were completed in 1988 [6]. Results from these earlier test series, along with other benchmark criticality tests conducted using materials similar to those that may be applied in a space reactor design, can be applied in current space reactor design and analysis to minimize the amount of nuclear testing required to validate the reactor design and to establish the design margins.

A joint NASA and Department of Energy (DOE) team is currently conducting nonnuclear testing of a fission surface power (FSP) system designed to produce approximately 40 kWe power via Stirling power conversion. The conceptual FSP system could be used in human missions to the lunar or Martian surface. Both of these applications have been studied by the FSP team, which has provided mission-compatible configuration options to the Lunar Architecture Team (LAT2) and the Mars Architecture Team (MAT). The LAT2 developed an FSP-based architecture referred to as Option 6 for a polar lunar outpost at the Shackleton Crater site (Fig. 3a). The MAT reviewed power system options for a crewed mission to Mars. The MAT-based FSP concept was directly extensible from the lunar concept (no power system design changes); however, it assumed that the reactor would be sited an above-grade mobile cart with integral shielding that would be robotically deployed from the lander (Fig. 3b) [7].



(a) (b)

Figure 3. Notional nuclear-based surface power architectures developed by the Lunar and Mars Architecture Teams: (a) LAT2 Option 6, buried FSP system for a polar lunar outpost at the Shackleton Crater site; and (b) Mars FSP concept on an above-grade mobile cart with integral shielding.

The initial concept definition for the fission surface power system, which could provide power to a manned or unmanned outpost on the moon, Mars or asteroid surface, identifies key requirements for the reactor module and balance of plant [6]. The report documents the "Pre-Phase A" FSP design, which will continue to evolve as requirements are better defined and hardware testing is completed. The preliminary reference concept includes a liquid-metal cooled, fast-spectrum reactor with Stirling power conversion and water-based heat rejection. The FSP would operate for a minimum 8-year service life with a minimum of 40 kWe net power. The conceptual reactor module uses highly enriched UO_2 fuel pins in a hexagonal core matrix with an external radial reflector and control drums; primary heat transfer from the core to the Stirling power convertors is provided via a pumped liquid metal (sodium-potassium (NaK) eutectic) cooling loop. Reactivity control is accomplished via external Be / B_4C control drums, taking advantage of the high neutron leakage and resulting high reflector worth in an FSP-class reactor. Cost and development risk are reduced by adopting stainless steel for all core structure and coolant piping, and the beryllium reflector is encased in a stainless steel shell. Additional details and justification for the selection of these materials and components are included in the concept definition document [7].

A nonnuclear, electrically heated Technology Demonstration Unit (TDU) describes an integrated system test that will be conducted at NASA Glenn Research Center (GRC) in 2012. The TDU is based on a conceptual system design, and additional design activities are continuing for the reactor module and other system components. The notional layout of the TDU hardware in NASA GRC vacuum facility #6 is shown in Fig. 4. TDU components are currently being fabricated and tested, including a reactor simulator, which incorporates heater elements to simulate nuclear fuel pins (Fig. 5a); annular linear induction pump (ALIP), designed to pump the liquid metal coolant; Stirling engines for power conversion, designed and built by industry partner Sunpower (Fig. 5b); and titanium water heat pipe radiators to emit waste heat.

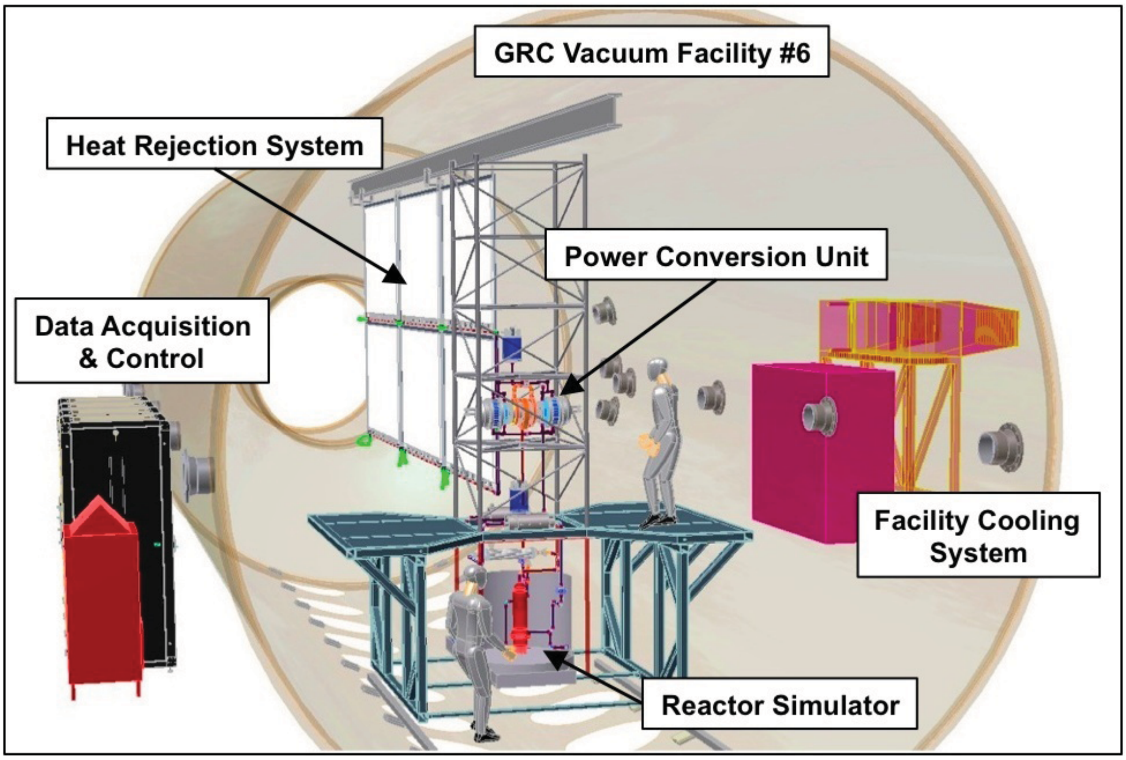
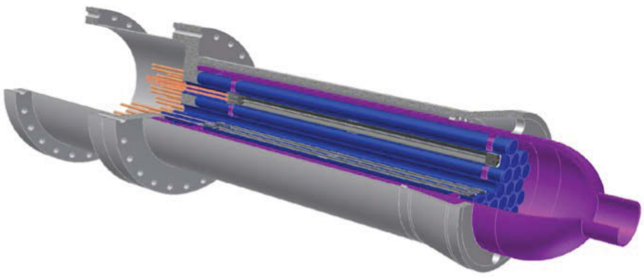
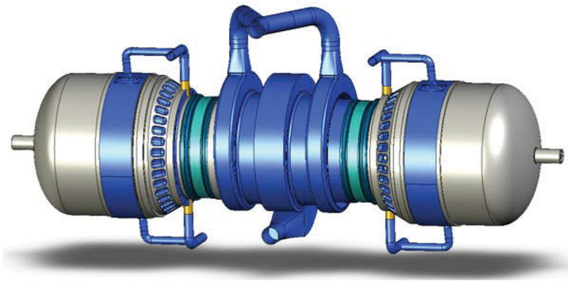


Figure 4. Notional Layout for Technology Demonstration Unit at NASA GRC.



(a)



(b)

Figure 5. TDU Components: (a) Core Simulator, and (b) Power Conversion Unit.

The TDU will establish the technology base for fission surface power systems, but technology developed within the FSP program will also provide a basis for future development of lower or higher power systems that could be applied in surface power or nuclear electric propulsion. A kilowatt-class fission power system, which could be a potential alternative to radioisotope power systems for deep space missions that push the limits of current RPS designs, has also been studied recently by a joint NASA – DOE team. The notional set of requirements applied in the brief study included 1-kWe output, 15-year design life, and 2020 launch availability. Brief concept screening studies led to the selection of a single concept for further feasibility analysis. The selected concept adopted a monolithic U-Mo reactor core, sodium heat pipes for core cooling, and distributed thermoelectric power converters directly coupled to aluminum radiator fins [8]. The notional system design is depicted in Fig. 6.

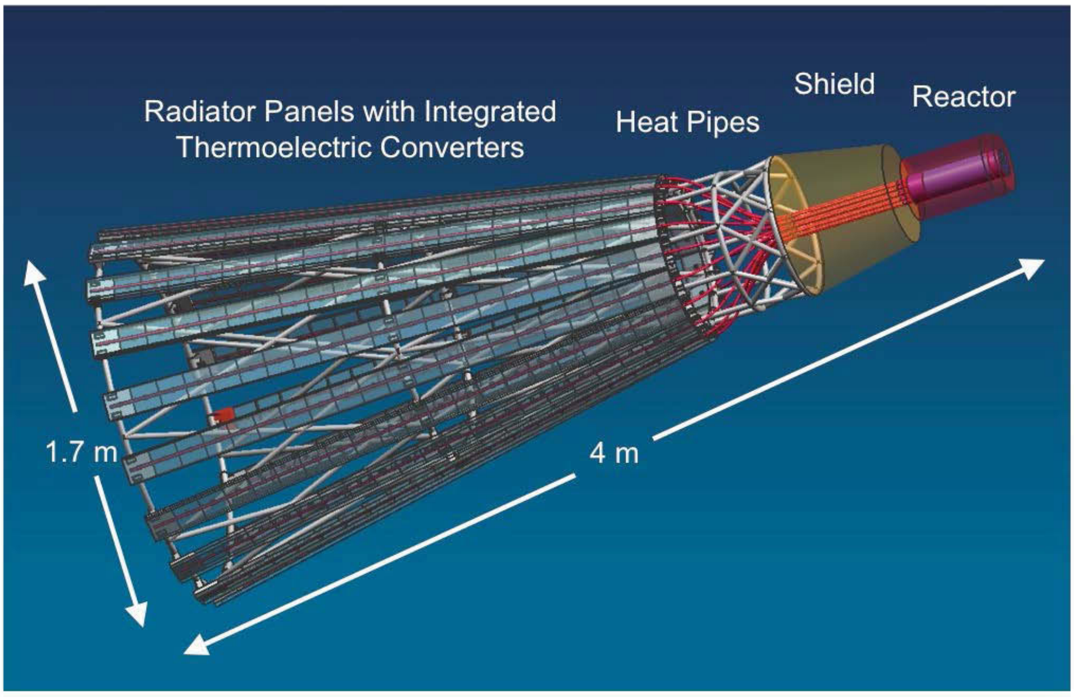


Figure 6. Conceptual Kilowatt-Class Fission Power System.

4. NUCLEAR PROPULSION SYSTEMS DEVELOPMENT

Significant research has been conducted for both nuclear electric and direct nuclear thermal propulsion systems. To date, however, neither type system has evolved to a flight program.

4.1. Nuclear Electric Propulsion

The Jupiter Icy Moons Orbiter (JIMO) program, a part of the larger Project Prometheus, sought to develop a nuclear electric propulsion system that would provide sufficient power to tour the Jovian moons Callisto, Ganymede, and Europa. The overall program was a collaboration between various DOE laboratories, NASA centers, Naval Reactors, industry and academia. The Naval Reactors Prime Contractor Team (NRPCT) led work on the development of the reactor plant system. Baseline requirements were for a 200 kWe reactor system capable of a 15-20 year mission and applicable to NEP. The program extensively reviewed several candidate reactor and power conversions system alternatives, leading to selection of a direct gas Brayton reactor plant for further development just prior to program cancellation. Despite the short program duration, substantial progress was made on defining reference plant operating conditions, defining reactor mechanical, thermal and nuclear performance, developing an understanding of power conversion options, reviewing performance and uncertainties associated with material selections, and planning for nonnuclear and nuclear system testing. Prior to program closeout, several nonnuclear, component level tests had been conducted, and initial nuclear testing of component materials in a fast reactor environment had commenced [9]. Although the program was not brought to completion, work conducted under the Prometheus Project was extensively documented to better position the US for future space reactor development.

A current study being conducted by NASA under the Enabling Technology Development and Demonstration (ETDD) Program, considers the feasibility of using NEP for a piloted mission to a near Earth object (NEO). The 300 kWe NEP vehicle concept, shown in Fig. 7, was developed for initial cost, mass, and performance capability comparison to a solar electric propulsion (SEP) vehicle performing the same mission. The NEO mission includes an un-crewed low Earth spiral of the electric propulsion (EP) stage to Earth-Moon Lagrange Point 1, where a 4-person crew stage rendezvous' and docks to the EP stage. The EP stage delivers the crew to the NEO for a 30-day science mission and returns them to Earth in approximately 400 days. Despite favorable Earth orbital (1 AU) sunlight conditions for SEP, the NEP vehicle performs the same mission with the same launch mass allocation, and also provides a credible development path for higher-powered EP missions to Mars and beyond. The NEP fission power system is based on an evolutionary advancement of the FSP technology that will be ground tested in the TDU and draws heavily from the previous JIMO program. The notional concept adopts a lithium-cooled, refractory alloy reactor with UN fuel, Brayton power conversion, water-based heat rejection radiators and AC power distribution to accomplish the mission.

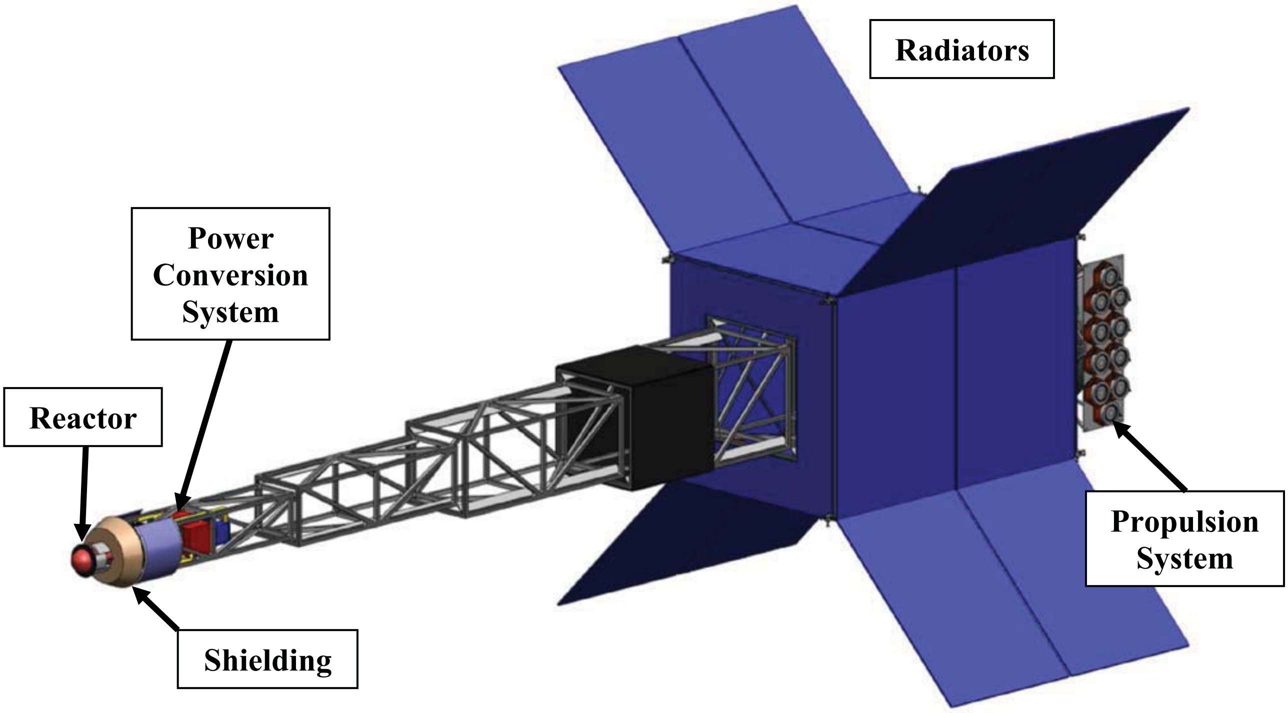


Figure 7. Conceptual 300 kWe Nuclear Electric Propulsion System.

4.2. Nuclear Thermal Propulsion

The future of space exploration depends on the ability to rapidly and economically access locations of interest throughout the solar system. A significant amount of design, development and nuclear testing was conducted for nuclear thermal propulsion (NTP) systems in the 1960s and 1970s in both the US and former Soviet Union. Repeated system studies and mission analysis of NTP systems indicate that NTP is the most technically mature, advanced propulsion system that can enable this access by providing a significant increase in capabilities over traditional chemical propulsion systems [10].

The Rover nuclear rocket development program, which commenced in 1955, led to the design, fabrication and nuclear testing of several nuclear rocket designs. Also referred to as the Nuclear Engine for Rocket Vehicle Application (NERVA) program, this program ran for approximately 20 years. Much of the data developed during the NERVA program and subsequent programs are being applied to guide the current NTP development path.

Current NTP work, which involves team members from DOE, NASA, industry and academia, seeks to capture historical design and performance data, recapture materials fabrication technologies and develop new fabrication techniques, enhance neutronics and thermal hydraulics design tools (e.g. develop NTP-specific multi-physics design and analysis tools), and design test strategies that can be used to test NTP components and systems in a safe, environmentally conscious manner. Predicted fuel and reactor system performance, based on previous test data and model predictions, should be verified experimentally prior to system launch. Key areas of interest include fuel performance at NTP operating temperatures (~2700 K fuel temperature), hydrogen coolant / propellant compatibility with fuel and structural materials, fission product retention, and reactor restart capability following system operation and shutdown for some period of time. The NTP team is currently reviewing fuel fabrication expertise, facilities, and capabilities for candidate NTP fuels at the Idaho, Oak Ridge, and Los Alamos National Laboratories; nonnuclear testing options for testing of fuel elements and materials in a realistic, hot hydrogen environment at NASA Marshall Space Flight Center; and nuclear testing options for component and system tests, which would require establishment of new test facilities [10].

5. CONCLUSIONS

Although many programs and projects are making progress in nuclear systems development, limited budgets and budget forecasts force development and implementation of these systems to take a slow path of progression. However, the benefit of nuclear technology is clearly evidenced in the dozens of successful RPS missions, and mission designers are generally enthusiastic about higher power capabilities, longer lifetimes, and shorter transit times offered by nuclear systems. It is encouraging that nuclear systems continue to be funded, albeit at a relatively low level, and space nuclear researchers will continue to make strides toward developing flight systems that could change the way we see our solar system – and eventually our universe.

ACKNOWLEDGMENTS

This review paper reflects the work of countless individuals over several decades. Their dedication to the development of space nuclear systems have enabled missions to the outer reaches of our solar system, and will enable mankind to accomplish even more compelling and demanding missions in the future.

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